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Abstract. The structure of the neutron-rich odd-even nuclei $^{37,39}_{15}P_{22,24}$ and $^{43,45}_{17}Cl_{26,28}$ nuclei has been investigated through in-beam γ-ray spectroscopy using the fragmentation of a 60.3·A MeV ^{48}Ca beam on a thin Be target. Level schemes as well as spin assignments are proposed for the nuclei studied in the present work. The experimental data are compared to shell model calculations and related to the onset of collectivity within the sd orbitals around N=28.

PACS. 21.10.Hw Spin, parity, and isobaric spin – 23.20.Lv Gamma transitions and level energies – 27.40.+z $39 \leq$ A ≤ 58 – 21.60.Cs Shell model

1 Introduction

In the last few years, large efforts were devoted to the study of the evolution of the N=28 shell gap between the neutron $f_{7/2}$ and $p_{3/2}$ orbitals, as the neutron to proton ratio is increased. According to beta-decay [1] and Coulomb excitation [2] experiments for nuclei near N=28, an onset of quadrupole deformation of the ground states is observed at Z=16. The study of the neutron-rich $^{40-44}$S using the in-beam γ-spectroscopy technique [3] suggested a deformed ground state for ^{40,42}S and a mixture of spherical and deformed configurations for ^{44}S. These features are in accordance with both the mean field [4–8] and the large-scale shell model calculations [9]. The decrease of the energy of the $3/2^-_1$ state from ^{47}Ca, ^{45}Ar [10] to ^{43}S [11] shows the development of quadrupole proton-neutron correlations and a gradual transition from spherical to deformed shapes. The role of protons for the development of the collectivity around N=28 was emphasized in Refs. [9, 12]. The increase of collectivity could be traced back from the gradual decrease of the $\pi s_{1/2}$–$\pi d_{3/2}$ energy from N=20 to N=28. As evidenced in the $_{19}$K isotopic chain [13], these orbitals become eventually quasi-degenerated at N=28. The study of the $^{37,39}_{15}P_{22,24}$and $^{43,45}_{17}Cl_{26,28}$ isotopes was intended to see to what extent and how this effect takes place in the Z=15,17 isotopic chains. The structure of the heavy P and Cl nuclei has already partly been investigated. The ^{37}P was studied by multi-nucleon transfer reaction [15], from which energies of several excited states have been deduced. The Coulomb-excitation of the ^{39}P and ^{45}Cl isotopes has been achieved at intermediate energy [16]. This provided the energy of an excited state directly connected to the ground state in both nuclei. Furthermore, several γ-transitions have been observed in ^{43}Cl through the β-decay of ^{43}S [17]. However, no level scheme could be deduced.

We have shown in Ref. [18, 19] that in-beam γ-spectroscopy of fragmented projectile-like nuclei is an efficient method for studying excited states in light neutron rich nuclei. It is complementary to other means mentioned above. In the present work we apply this method to explore the structure of the neutron rich odd-proton ^{37,39}P and ^{43,45}Cl nuclei. Henceafter we expect to obtain a more global understanding of the structure of these odd-Z nuclei.

2 Experimental methods

The neutron-rich ^{37,39}P and ^{43,45}Cl have been produced at GANIL by the fragmentation of a 60.3A·MeV ^{48}Ca beam, of mean intensity of 15 enA, on a ^{9}Be target of 2.76 mg/cm^2 thickness. The SPEG magnetic spectrometer was operated in a dispersive mode to identify the emerging fragments detected at the focal plane. Their energy losses and positions in the focal plane were determined by the combination of ionization and drift chambers. Their residual energies were obtained in a thick plastic scintillator. The time of flight was derived from the timing signals in the plastic scintillator with respect to the cyclotron radio frequency. It was corrected by the use of the position of the fragments in the focal plane of the SPEG spectrometer to obtain a better time resolution and subsequently a better identification of the nuclei.

A total of 25·10^6 nuclei were detected in the focal plane of the SPEG spectrometer and well separated ^{43,45}Cl and ^{37,39}P isotopes were collected in amounts of 3 to 50·10^3.

The target was surrounded by an array of 74 BaF_2 and 3 segmented Ge clover detectors to identify the γ-rays emitted in flight by the excited fragments. The BaF_2 detectors were mounted symmetrically above and below the target at a mean distance of 16 cm, covering ∼80% of the total solid angle yielding a total photo-peak efficiency of 25% at 1.33 MeV. This large efficiency detector set-up was mainly used to obtain $\gamma\gamma$-coincidences. The 3 segmented Ge clover detectors placed at 15 cm from the target at angles of 85°, 122° and 136° with respect to the beam direction were used to determine the energy of the transitions with a better accuracy. Their summed efficiency is 0.7% at 1.33 MeV. The γ-ray energy spectra have been corrected for the Doppler-shift caused by the large velocity $v/c \simeq 0.34$ of the fragments. Doppler broadening arising from the finite solid angle of the detectors has been reduced in our case by utilizing the segmentation of the crystals of the clover detectors. Consequently, the full width at a half maximum is ∼35 keV for a γ-ray of 1570 keV. The energy threshold of the Ge detectors was set to about 200 keV, which corresponds to a value of about 300 keV for the Ge detector at backward angle.

The segmented Ge detectors at 85, 122 and 136° to the beam allows for angular distribution measurements even at 16 cm distance to the target. The intensity ratios for pairs of angles are non-isotropic and are consistent with a spin orientation of 30 to 70% [20] for these nuclei produced in a fragmentation reaction.

By normalizing these ratios to those of the 1570 keV stretched E2 transition of ^{46}Ar [21,22] produced in the same spectrometer setting we find that they cluster into two groups corresponding to stretched quadrupole and stretched dipole transitions as shown in Fig. 1 and in Refs. [3,10]. This information has been used to deduce spin-values of the levels.

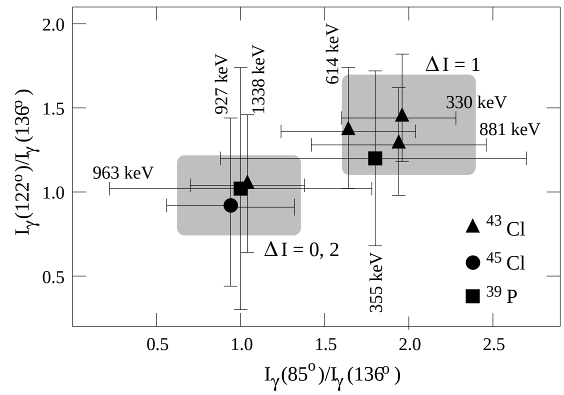

Fig. 1. Angular anisotropy ratios are shown for the γ-transitions in ^{39}P and ^{43,45}Cl. The hatched areas delimit two zones which correspond to stretched quadrupole and dipole transitions.

From the study of nuclei whose levels schemes were previously known we deduce that the feeding of excited states with respect to the ground state is fairly constant around 80%. This ratio has been used as a sum rule to help constructing the level schemes.

3 Experimental results

The γ-ray spectra of ^{37,39}P obtained in the Ge clover detectors are presented in Fig. 2.

The spectrum for ^{37}P shows one strong transition at 868(7) keV. The strength of the 868 keV transition suggests that it de-exites a level at this energy directly to the ground state which is in accordance with the ^{36}S(^{18}O,^{17}F)^{37}P results of Ref. [15].

Four transitions are observed in ^{39}P at 355(6), 619(7), 963(6) and 1201(9) keV. The 355 keV transition which is the strongest is assigned to the first exited state and the 963 keV transition which within the experimental errors coincides with the sum of the 355 and 619 keV transitions, defines a level at 966 keV as shown Fig. 3. Tentatively the 1201 keV transition is placed as populating the 966 KeV level from a level at 2167 keV. The angular anisotropies shown for the 355 and 963 keV γ-rays in Fig. 1 agree with a ΔI=1 and a ΔI=0,2 transitions respectively. For the 963 keV line this corroborates the previous [16] E2 assignment from a Coulomb excitation measurement at intermediate energy. The intensity sum of the two transitions furthermore provides the expected γ-ray strength per nucleus produced. The expected ground state spin of this Z=15 nucleus is $1/2^+$ and we therefore deduce the sequence $1/2^+$, $3/2^+$, $5/2^+$ for the lowest levels as shown in Fig. 3.

The B(E2:g.s $\rightarrow$ 966 keV) value has been deduced in Ref. [16] from the intensity of the 963(6) keV transition to be 97(30) e^{2}fm^4. Considering that about 40% of the decay from this level also occurs through the 355 and 619 keV lines, the B(E2) value should be scaled to take this missing

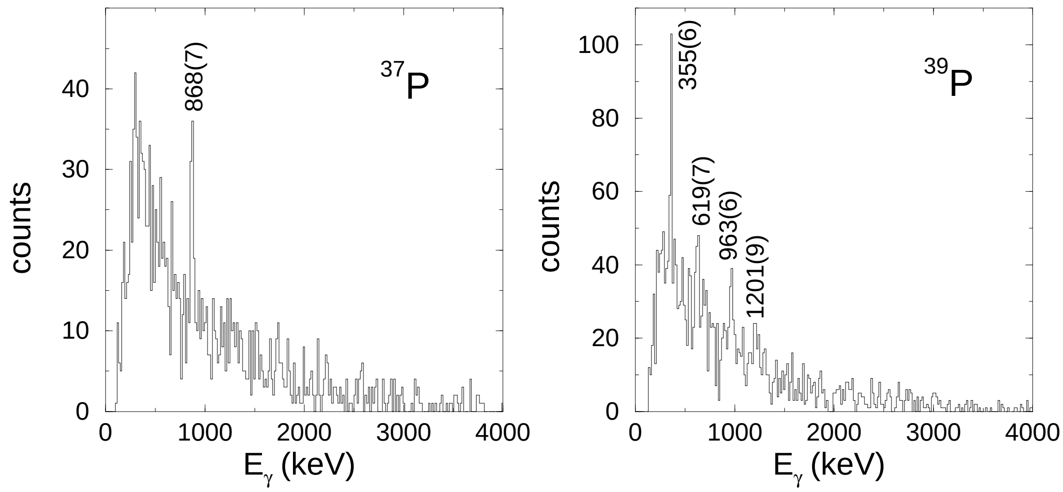

Fig. 2. Germanium γ-ray spectra of ^{37}P and ^{39}P nuclei produced in fragmentation of ^{48}Ca.

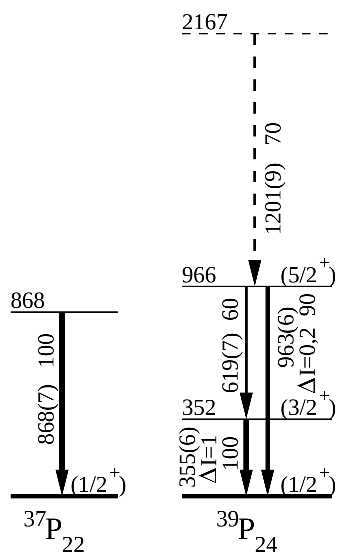

Fig. 3. Level schemes deduced for ^{37,39}P from the present work. Along the γ-lines their energies (with uncertainties), multipolarities and their relative intensities are given.

strength into account This leads to B(E2:g.s $\rightarrow$ 966 keV)= 136(40) e^{2}fm^4 for ^{39}P.

In ^{43}Cl four γ-lines of 330(5), 614(5), 881(5) and 1338(6) keV energy are observed with the Ge clover detectors, as shown in Fig. 4 left. An additional one at 1509(10) keV is found with a 2.5σ confidence level. The four lowest transitions were observed in the β-decay of ^{43}S [17]. The present energies are in a good accordance with the ones obtained from the β-decay study. The $\gamma\gamma$-coincidence spectrum gated on the 330 keV γ-line is shown in the insert of Fig. 4. From the analysis of the coincidence spectra we find that the 330, 614 and 881 keV transitions are in mutual coincidences. The 330 keV transition has the highest intensity. We therefore assume that this transition arises from the decay of the first excited state to the ground state. The 614 and 881 keV transitions are placed above, considering their $\gamma\gamma$-coincidence relationships. Their ordering is determined by their respective intensities. The 1509(10) keV γ-energy overlaps with the sum of the 614(5) and 881(5) keV transitions within the present uncertainties on the energies. Consequently, it is tentatively considered as a cross-over transition. The integrated γ-ray intensity of the 1509 and the 881 - 614 keV cascade is smaller than the one expected from the ratio to the number of ^{43}Cl nuclei produced. We suggest, as shown in Fig. 4, that the 1338 keV transition, most probably an E2 (see Fig. 1), feeds the ground state directly and accounts for a part of the missing intensity. The angular anisotropy ratios of the 330, 614, 881 keV γ-rays correspond to stretched dipole transitions as shown in Fig. 1. The ^{37}Cl and ^{39}Cl ground state spin values are $3/2^+$, their first excited state are $1/2^+$. The energy difference E($1/2^+$-$3/2^+$) sharply decreases in ^{39}Cl suggesting that an inversion between these two levels could occur in ^{41}Cl. From the experiment of Liang et al. [23] which produced the ^{41}Cl through an Yrast feeding, it has been surmised that its g.s. spin value is probably $1/2^+$. From this trend of spin values in the Cl isotopic chain, we also expect an $1/2^+$ g.s. spin in ^{43}Cl rather than a $3/2^+$. In addition, the observed anisotropy of the 330 keV transition rules out the possibility that this transition could arise from the decay of a $1/2^+$ excited state. Consequently, we deduce in ^{43}Cl a sequence of levels ($1/2^+$:g.s.), ($3/2^+$:330 keV), ($5/2^+$:946 keV) and ($7/2^+$: 1830 keV) connected by M1 transitions from the γ-ray angular distribution information. The 1338 keV level would have a $5/2^+$ configuration.

Fig. 4 right shows the γ-ray spectrum of ^{45}Cl. It exhibits two γ-rays with energies of 927(7) and 1616(8) keV. The lower energy γ-ray was observed in the Coulomb excitation of ^{45}Cl [16]. Based on the facts that the 927 keV line has the highest intensity and was observed in the Coulomb-excitation experiment we surmise that the 927 keV γ-ray decays - at least partly - directly to the ground state. Assuming a $1/2^+$ ground state, a spin and parity $5/2^+$ is proposed for the level at 927 keV of ^{45}Cl from the γ-ray angular anisotropy ratio information (Fig. 1). Similar to the case of ^{43}Cl, the γ-transition of 1616 keV is placed in

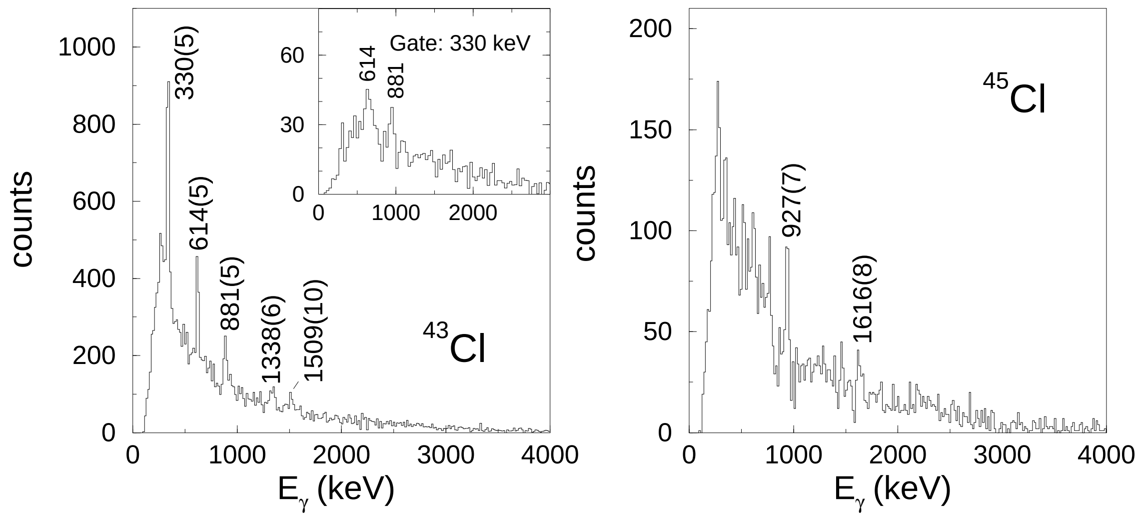

Fig. 4. Germanium γ-ray spectra of ^{43}Cl and ^{45}Cl nuclei produced in fragmentation of ^{48}Ca. The insert in the left-hand figure shows a γ-γ coincidence spectrum by BaF$_2$ detectors gated on the 330 keV transition.

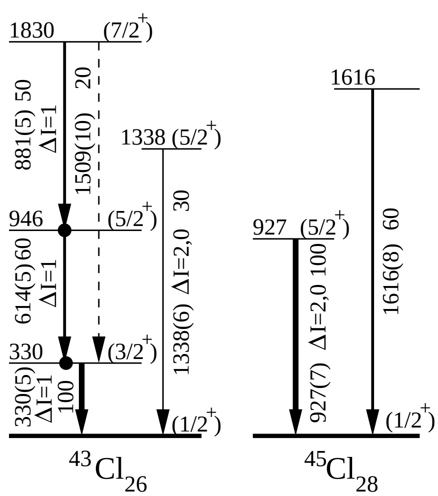

Fig. 5. Level schemes proposed for ^{43,45}Cl from the present experiment. The energies (with uncertainties), multipolarities and relative intensities are given for each γ-ray transition.

parallel on the basis of the expected rate of nuclei produced in excited states. Some other transitions may be seen between 300 keV and 927 keV but the present statistics is too weak to ascertain this hypothesis.

4 Discussion

To interpret the experimental results we have performed shell model calculations. An inert core of $^{28}_{8}O_{20}$ has been used, with a valence space composed of the *sd* orbitals for the protons and of the *fp* ones for the neutrons. We have used the interaction developed in Ref. [24]. The experimental level schemes obtained for the ^{37,39}P and ^{43,45}Cl nuclei are compared to shell model calculations in Figs. 6 and 7.

The shell model calculations reproduce with less than 10% energy difference the measured first excited state of ^{35}P. In ^{37}P the first excited state lies at 0.868 MeV. Shell model calculations give $3/2^+$ and $5/2^+$ states at 1.20 MeV and 1.74 MeV, respectively. In ^{39}P, the calculated energies of the $3/2^+$ and $5/2^+$ states are 0.64 and 1.27 MeV. In both cases calculations overestimate the energy of the excited states by 300 to 400 keV. This discrepancy between the measured and calculated energies of the excited states in the P isotopes can be traced back to the $f^2_{7/2}$ matrix elements since the calculated 2^+_1 states in the N=22 isotones $^{36}_{14}$Si and $^{38}_{16}$S exhibit too high energy as compared to experiment. One reason could be that the *fp* part of the effective interaction, borrowed from Ref. [26] was adjusted from a ^{40}Ca core while the effective neutron-neutron interaction in our study is applied to an ^{28}O core.

In the Cl isotopic chain the overall agreement between the experimental and calculated energies, spins and γ-ray branching ratios is satisfactory. The energies of the yrast states in the ^{41}Cl nucleus were obtained by Liang et al. [23] using deep inelastic collisions. In ^{43}Cl the yrast cascade is also well reproduced. The calculations also show that the decay of the $7/2^+_1$ state would occur through competition of E2 and M1 transitions to the $3/2^+_1$ and $5/2^+_2$ states, respectively. However, it is predicted that the E2 strength is larger (60% against 40%), contrary to what we find (30% against 70%). In ^{45}Cl, we find a $5/2^+_2$ state close in energy to the calculated one. The present statistics does not permit us to firmly establish the non/existence of a lower energy state.

The study of these odd-proton P and Cl nuclei provides the opportunity to access the role of protons in triggering the deformation in the region of ^{42}S. In particular, the differential interaction acting between the $f_{7/2}$ neutrons and the $d_{3/2}$ and $s_{1/2}$ protons gives rise to a decrease of the $\pi s_{1/2} - \pi d_{3/2}$ energy difference as the neutron orbital $f_{7/2}$ is filled up to N=28. In the K isotopic chain, this measured energy difference decreases from 2.5 MeV in $^{39}_{19}K_{20}$

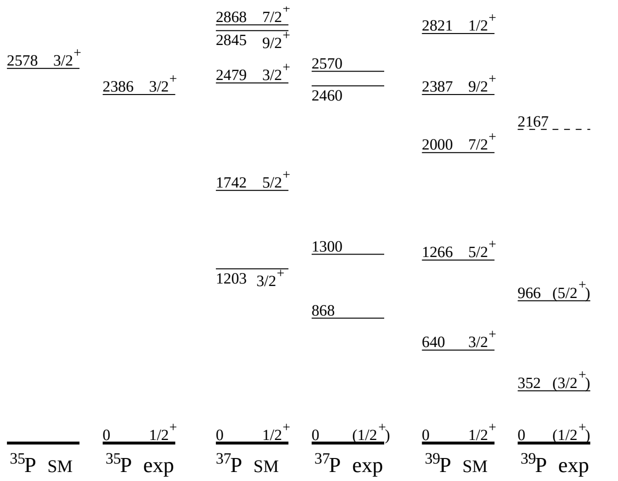

Fig. 6. Comparison between the experimental (exp) and calculated level schemes (from shell model) for the P isotopes. The experimental data for ^{35}P are taken from Ref. [25]. Those for the states at 1300, 2460 and 2570 keV in ^{37}P are taken from Ref. [15].

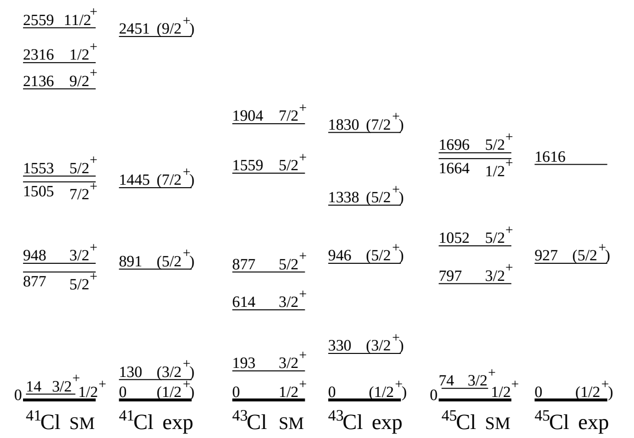

Fig. 7. Comparison between the experimental level schemes and the ones deduced from shell model calculations for the Cl isotopes. The experimental data for ^{41}Cl are taken from Ref. [23].

to few tens of keV in $^{47}_{19}K_{28}$ [13]. Similar effect is found in the Cl and P isotopic chains when looking at the effective single particle energies deduced from the shell model calculations.

The calculated ground state spin of ^{35,37,39}P is $1/2^+$. It corresponds to the normal ordering of the filling of the proton orbitals in the P case. The calculated B(E2:$1/2^+ \rightarrow 5/2^+$) of ^{39}P is 153 e^{2}fm^4. It agrees well with the experimental value of 136(40) e^{2}fm^4 deduced from the combination of the present study and of that of [16] (see the discussion in the previous paragraph). In the Cl isotopes the $s_{1/2}$ orbit is filled up and an additional proton is placed in the $d_{3/2}$ shell, leading to a $3/2^+$ state. This is true up to ^{41}Cl after which the ordering of the $3/2^+$ and $1/2^+$ states is exchanged. The decrease of the $\pi s_{1/2} - \pi d_{3/2}$ single particle energy difference makes the pairing more effective as neutrons are added up to N=28. This favors a configuration where two protons are coupled to zero into the $d_{3/2}$ orbital, generating a hole in the $s_{1/2}$ shell which gives the $1/2^+$ configuration of the ground state. In this case the occupation probability of the two orbits is nearly the same (0.5) resulting in nearly degenerated quasi-particle states. These quasi-particles subsequently couple to the quadrupole excitations provided by the core. As a result, both the $1/2^+$ and $3/2^+$ states of ^{41,43,45}Cl become a mixture of quasi-particle and quasi-particle coupled to the 2^+-phonon configurations. Since these states have quite a complicated wave function, it is quite difficult to draw any conclusion from their energy systematics only.

5 Summary

The in-beam γ-spectroscopy technique has been used to study the excited states of the odd-proton nuclei ^{37,39}P and ^{43,45}Cl from the fragmentation of a ^{48}Ca beam. The results obtained have been compared with shell model calculations. These calculations reproduce the quasi-degeneracy of the $s_{1/2}$ and $d_{3/2}$ proton orbitals when the $f_{7/2}$ neutron orbital is filled. Good accordance in the case of ^{43}Cl and a slight discrepancy in the case of P isotopes are found between calculated and measured energy of the excited states. This discrepancy can be traced back to the deficiency of the effective neutron-neutron interaction used.

The experiment using in-beam γ spectroscopy with fragmentation reactions benefits from the availability of ^{48}Ca isotope kindly provided by our colleagues from Dubna and from the smooth running of the accelerator by the GANIL crew. The use of the segmented clover detectors was made possible thanks to the EXOGAM Collaboration. This work has been supported by the European Community contract N° HPRI-CT-1999-00019, OTKA-D34587, T030497, T038404, GA ASCR A1048 102 and by the Bolyai János Foundation. We thank S. Grévy for fruitful discussions.

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